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Evaluation of ECMWF cloud type simulations at the ARM Southern Great Plains site using a new cloud type climatology

George Tselioudis[1] and Pavlos Kollias[2]

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[1] A new method to derive a cloud type climatology is applied to cloud observations over the Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) site and to ECMWF model forecasts, in order to compare model and radar derived cloud type statistics and identify the major deficiencies in model cloud vertical distribution. The results indicate that cirrus and to a lesser extent middle level clouds are the major cloud types missing in the model simulations and that they are missing mostly as parts of multi-type rather than single-type structures. Boundary layer clouds are simulated at approximately the right amounts in the annual mean statistics, but this result comes from the model simulating too little boundary layer cloud in the winter and too much in the summer. Overall, the model forecasts miss about 11% of the total cloud amount, and most of the missing cloud occurs at time periods when multiple cloud types are present in the observations. **Citation:** Tselioudis, G., and P. Kollias (2007), Evaluation of ECMWF cloud type simulations at the ARM Southern Great Plains site using a new cloud type climatology, *Geophys. Res. Lett.*, *34*, L03803, doi:10.1029/2006GL027314.

1. Introduction

[2] Evaluation of cloud fields in global models has relied primarily on satellite observations that provide global coverage and resolve seasonal and interannual variability. In the midlatitude regions, a recent evaluation of the European Center for Medium-Range Weather Forecast (ECMWF) model and the Goddard Institute for Space Studies (GISS) climate model against the International Satellite Cloud Climatology Project (ISCCP) satellite retrievals [*Tselioudis and Jakob*, 2002] showed that both models underpredict cloud amounts and overpredict cloud optical depths. The deficit in model cloud cover results from the inefficiency of the models in generating middle level clouds and is more pronounced in continental regions. Simulating too little middle level cloud is a general problem found in several studies that evaluate GCM clouds against satellite retrievals [*Webb et al.*, 2001; *Tselioudis and Jakob*, 2002; *Zhang et al.*, 2005]. It must be noted, though, that satellite retrievals of cloud properties provide radiative rather than physical cloud boundary definitions. Thus, the satellite-retrieved midlevel clouds can physically represent either clouds with tops in the middle levels or multi-layered cloud structures that emit in the infrared from the mid-troposphere. The studies cited above apply a satellite simulator to the model output in order to retrieve model cloud tops from their emission level, but their analysis does not clarify whether the model cloud underprediction is due to missing mid-level clouds or multi-layered cloud structures. The lack of such knowledge makes it hard to transition from the identification of model cloud deficiencies to the improvement of model cloud simulations.

[3] Cloud layering information at present can be derived at near-global scales from radiosonde relative humidity profiles [*Wang et al.*, 2000; *Rossow et al.*, 2005] and at local scales from cloud radar retrievals [e.g., *Dong et al.*, 2000; *Clothiaux et al.*, 2000]. The midlatitude continental location of the ARM program [*Stokes and Schwartz*, 1994; *Ackerman and Stokes*, 2003] Southern Great Plains (SGP) site and the available multi-year cloud layering information provides an opportunity to derive statistical cloud layering information and evaluate model simulations of midlatitude cloud vertical structure. A cloud layering climatology from ARM SGP data is presented by *Kollias et al.* [2007] where it is shown that while mid-level clouds occur relatively infrequently as single layers they occur more frequently in combination with other cloud types. Model output analysis over the SGP site to derive similar statistical cloud layering results would provide valuable information on the vertical structure of model midlatitude cloud fields and would help clarify the reasons for model cloud layering deficiencies. In this study we analyze such output from the ECMWF model forecasts, since a version of that model was used in the *Tselioudis and Jakob* [2002] study. The main objective is to compare model and radar derived cloud type statistics, in order to identify the major model deficiencies in cloud vertical distribution and map their seasonal variations. In addition we examine whether potential model deficiencies in producing middle level clouds come from the simulation of clouds physically located in the middle troposphere or from multi-layer cloud structures with mid-tropospheric radiative signatures.

2. Methodology

[4] The Active Remote Sensing Cloud Locations (ARSCL) [*Clothiaux et al.*, 2000] value added product combines the Millimeter Cloud Radar (MMCR), the Vaisala Ceilometer and the Micropulse Lidar (MPL) observations at the ARM Climate Research Facilities (ACRF) and provides the most accurate representation of cloud layering with a temporal resolution of 10 sec and vertical resolution of 45 m [*Clothiaux et al.*, 2000; *Kollias et al.*, 2005]. *Kollias et al.* [2007] used long-term (6.5 years, January 1998–July 2004) ARSCL observations from the SGP ACRF site in Oklahoma

[1]NASA Goddard Institute for Space Studies and Department of Applied Physics, Columbia University, New York, New York, USA.

[2]Atmospheric Science Division, Brookhaven National Laboratory, Upton, New York, USA.

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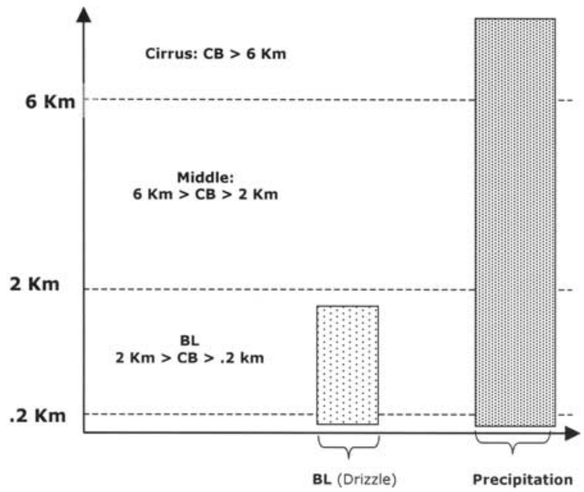

Figure 1. An illustration of cloud type definitions applied to both ARSCL observations and ECMWF model output.

to develop a cloud-type climatology. The objective was to take advantage of the detailed ARSCL cloud layering information and create a cloud-type climatology based on type definitions that relate to the major dynamic and thermodynamic cloud-formation processes at the SGP site. In this paper we apply a simplified version of the *Kollias et al.* [2007] methodology to create cloud type climatologies from the ARSCL observations and from the ECMWF hourly model output. On the observational side, a method is applied to the 10 sec ARSCL time series of cloud tops and cloud bases in order to classify instantaneous observations of clouds into the following categories: (1) boundary layer (BL) clouds when the cloud base is between 0.2 and 2 km or when the cloud base is below 0.2 km and the cloud top below 2 km (drizzle), (2) middle clouds when the cloud base is between 2 and 6 km, (3) cirrus clouds when the cloud base is above 6 km, and (4) precipitating clouds when the radar-lidar defined base [*Clothiaux et al.*, 2000] is below 0.2 km and the cloud top is above 2 km (Figure 1). Following the instantaneous cloud type classification, the percent coverage of each cloud type in a 20 minute period is derived (the reasons for the choice of the twenty minute interval will be explained in the final paragraph of this section). Note that for a cloud layer to be included in the calculation of the cloud cover it has to last a minimum of 5% of the time period (i.e. 1 minute), and that coinciding cloud layers of the same cloud type are counted as one occurrence. The identified cloud types are then classified in periods when a particular cloud type (e.g., cirrus, middle or BL) is the only layer observed (single-type periods) and periods when two or more cloud types are present (multi-type periods).

[5] The same analysis method is applied to output from ECMWF model forecasts of the same 6.5-year time period over the SGP site, to derive the equivalent cloud-type climatology from the model. The model output is available every hour for a grid box 111 by 152 km wide centered on the SGP site. Over the 6.5-year time period the ECMWF model used to produce the ARM output underwent some changes. Vertical resolution, for example, changed gradually from 30 to 60 pressure levels. However, the cloud type statistics produced by our methodology showed no discernable jumps or trends in their time series. It may be that the coarse vertical layers used for the cloud type definitions reduce the sensitivity of the statistics to changes in model parameters. The issue of evaluating a model grid output using column observations was examined in several studies [e.g., *Jakob et al.*, 2004]. Here we use an approach based on the ISCCP simulator software [*Klein and Jakob*, 1999] that can be used to statistically create sub-grid variability in model grid box cloud fields. We divide the "SGP" model grid box into 100 pixels (roughly 10 by 15 km each), use a maximum-random assumption (maximum for vertically contiguous layers random for non-contiguous ones) to overlap the cloudy layers, and then randomly select one of the pixels to be the one representative of the SGP column conditions. The approach attempts to create a spatial snapshot within the model SGP grid box to compare to the time snapshot captured by the SGP instruments. It creates subgrid scale cloud layering variability based on the overlap assumptions that most models use to calculate the radiative fields. Since the location of the SGP ACRF within the model grid box is not resolved, a random pixel is picked at each time step. When the use of more than 100 sub-grid pixels was tested, the cloud type statistics derived by this methodology did not change.

[6] Even with the introduction of some measure of subgrid scale variability, model output only provides the percent of time during the one-hour time step that a cloud type is present in the 10 by 15 km SGP grid box. Assuming a typical cloud propagation speed of 10 m/s it would take an instrument located in the center of the grid box about twenty minutes to observe the same sample of cloud types. This is the reason that the twenty- minute time step was used in the analysis of the ARSCL data. Given that the speed of the cloud systems over the SGP ACRF varies, we tested the sensitivity of this time-space comparison to the length of time of the radar snapshot that is used in the ARSCL analysis, starting with one hour and moving to periods as small as 10 minutes. The results indicate that the multi-year climatological features change by at most a couple of percentage points when we change the length of the radar time interval. It is important to note here that in this paper multi-type clouds are defined as time steps in the model and the observations that more than one cloud type is present. This definition is applied consistently between model and observed cloud types, and the analysis of *Kollias et al.* [2007] shows us that the derived single and multi-type cloud periods correspond to distinct dynamic regimes.

3. Results

[7] An illustration of the method applied to the ARSCL data to derive the different cloud types is presented in Figure 2, where a two day snapshot of the MMCR reflectivities is shown at the top and the coverage of the four basic cloud types as defined in Figure 1 is shown in the lower four panels. The time period selected includes a frontal passage from the SGP ACRF with typical structures of cirrus overlaying low clouds in the pre-frontal region, deep precipitating clouds along the frontal zone, and an extensive low cloud deck following the passage of the front. The cloud type distributions illustrate the presence of multi-type

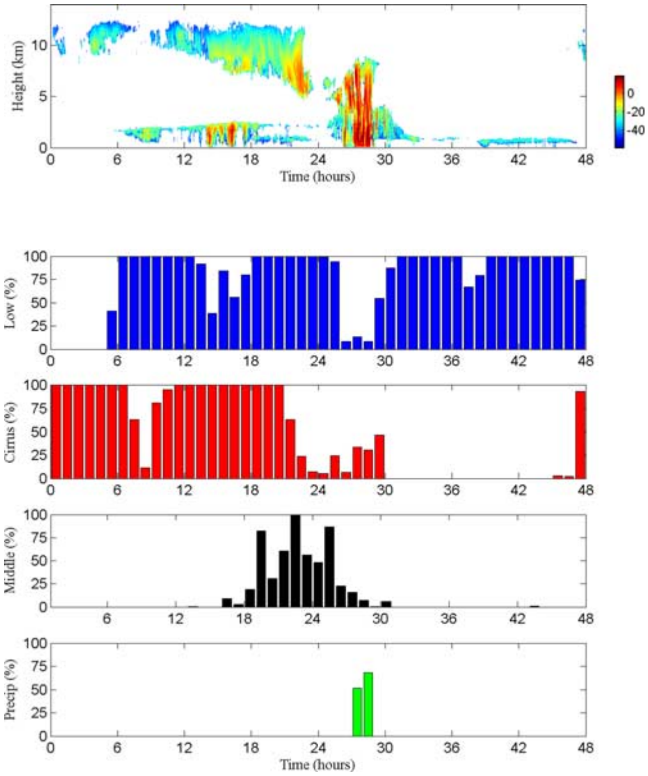

Figure 2. (top) Two-day snapshot of MMCR reflectivities and (bottom) the coverage of the four basic cloud types defined in Figure 1 for the same two day time period in December 2003.

cloud structures both at the pre-frontal and the frontal regimes and a post-frontal single-type cloud structure. Middle level clouds form in the pre-frontal regime as both upward extensions of the low cloud deck and downward extensions of the cirrus layer, and along the frontal zone as parts of the more fragmented structure of the deep cloud layer. The cloud structures in this one snapshot agree well with the structures of the cloud layering composite of midlatitude cyclones presented by *Rossow et al.* [2005].

[8] The model performance in simulating single and multi-type cloud structures is initially explored in Figure 3, which shows time series of daily fractional coverage by single-type cloud scenes (top) from ARSCL (red line) and ECMWF (black line) for January and February 2004, and the same time series for multi-type cloud structures (bottom). It can be seen that the model simulates fairly well the single-type time series while at times missing significant parts of the multi-type cloud structure. The 2-month average single-type fractional coverage is 33.9% in ARSCL and 31.0% in ECMWF, while the 2-month average multi-type fractional coverage is 19.6% in ARSCL and 10.8% in ECMWF.

[9] The results of the ARSCL and ECMWF model cloud type climatologies for the 6.5 years are summarized in Table 1. In the annual mean, the ARSCL-based retrievals show that 56.5% of the clouds appear as single types while 43.5% appear in multi-type periods. These numbers compare well with the radiosonde-based survey of *Wang et al.* [2000] that finds 58% single-layered and 42% multi-layered clouds globally and somewhat higher percentage of multi-layered clouds in the central US. When examining the model derived annual mean cloud type distribution of the combined single and multi-type structures, the model forecasts appear to be missing mostly cirrus (7.3%) and some middle level clouds (2.6%). Both the missing cirrus and middle layer clouds come primarily from the summer months. Boundary layer (BL) cloud amounts are simulated very well in the annual mean but this correct simulation comes from a winter underprediction combined with a severe summer overprediction. Precipitating clouds are underpredicted by 2% to 3% in both seasons.

[10] One advantage of the model evaluation method using cloud layering information is that it can partition the model cloud deficiencies into single and multi-type situations. In simulating single-type clouds structures, ECMWF underpredicts single cirrus clouds by 3.1%, showing a somewhat greater underprediction in the summer (4%) than in the winter (3.2%). The model overpredicts annual mean single BL amounts by only 0.8%, but does so by underpredicting them in the winter (3%) and overpredicting them in the summer (4.7%). Middle clouds occur as single layers 4.4% of the time in ARSCL, while ECMWF slightly overpredicts them (5.6%). Precipitating clouds occur rarely as single layers in ARSCL (1.1% annual) while they occur more often in ECMWF forecasts (2.4%). In total, ECMWF underpredicts single type clouds by only 2.5%.

[11] The ECMWF forecasts underpredict almost all multi-type cloud categories in all seasons. In the annual mean, the most severely underpredicted category is cirrus and middle clouds (3%) followed by triple-type cloud structures (2.6%) and BL and middle clouds (1.5%). This

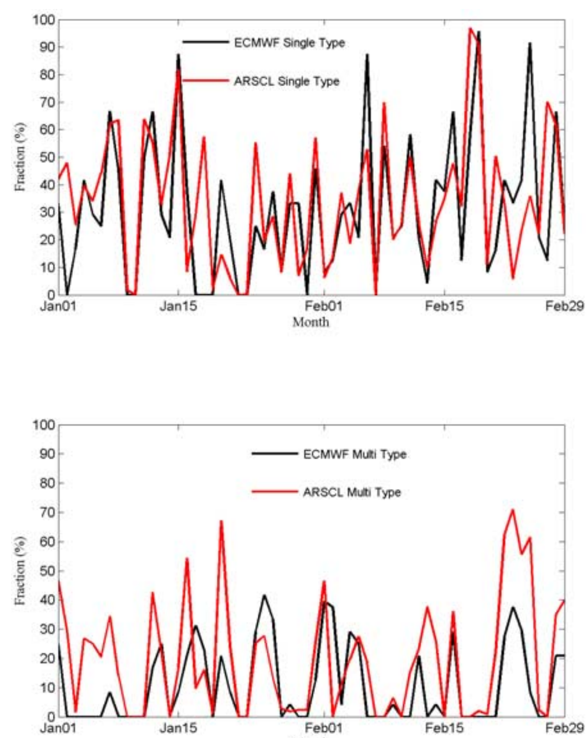

Figure 3. (top) Daily amounts of single-type and (bottom) multi-type cloud amounts from ARSCL data (red line) and ECMWF forecasts (black line) for January and February 2004.

Table 1. The 6.5-Year Climatology of Cloud Types From ARSCL and ECMWF Data

	NDJFM[a]		JJA[b]		Annual	
Cloud Type	ECMWF	ARSCL	ECMWF	ARSCL	ECMWF	ARSCL
Cirrus	22.4	28.1	23.2	34.6	22.9	30.2
Single Cirrus	13.3	16.5	12.5	16.5	12.4	15.5
BLC	16.1	21.5	15.4	6.6	17.1	16.1
Single BLC	6.4	9.4	7.5	2.8	7.6	6.8
Middle	18.5	19.4	12.9	16.2	15.4	18.0
Single Middle	7.7	4.3	5.0	4.4	5.6	4.4
Precipitation	5.6	7.9	3.4	6.6	5.2	6.5
Single Precipitation	1	3	0.7	3.8	1.1	2.4
Total Single	28.4	33.3	25.7	27.6	26.7	29.2
BLC and Cirrus	2.1	4.8	3.5	3.1	2.8	4.1
BLC and Middle	3.1	4.1	1.1	2.5	2.1	3.6
Cirrus and Middle	3.2	5.8	3.6	7.4	3.3	6.2
BLC, Middle, Cirrus	1.7	4.8	1.7	3.9	1.8	4.4
PR, Other	4.6	4.9	2.7	2.8	4.1	4.1
Total Multi Type	14.7	24.5	12.6	19.7	14	22.5
Clear Sky	56.6	42.2	61.4	52.7	59.2	48.3

[a]NDJFM, November, December, January, February, and March.
[b]JJA, June, July, and August.

ranking is also true in the summer months with values 2.8, 2.2, and 1.4% respectively. In the winter months, triple-type cloud structures are underpredicted most severely (3.1%), followed by BL and cirrus clouds (2.7%), and cirrus and middle clouds (2.6%). The multi-layer category of precipitating and any other cloud type is simulated with only tenths of a percent error in all seasons. Overall, in the annual mean the multi-type cloud structures are underpredicted by 8.5%, which means that they constitute the majority of the 11% total missing cloud in the ECMWF forecasts.

4. Discussion

[12] This paper introduces a methodology to construct a cloud type climatology from point radar data and from model grid output, and shows how the climatology can be used to evaluate cloud vertical distribution in model simulations. The results indicate that cirrus and to a lesser extent middle level clouds are the major cloud types missing in the model simulations and that they are missing more often as parts of multi-type rather than single-type structures. In the annual mean, boundary layer clouds are predicted at approximately right amounts by the model, and as single-layer structures, are even somewhat overpredicted in the model simulations. However, the correct simulation of annual mean amounts of BL clouds comes from simulating too little BL cloud in the winter and too much in the summer. Overall, the model misses about 11% of total cloud amount and most of the missing cloud comes from the simulation of multi-type cloud periods. Single-type cloud periods, such as post-frontal continental stratus clouds, are found by *Kollias et al.* [2007] to be associated with strong large-scale forcing such as subsidence and cold air advection, while the multi-type cloud scenes require a complex profile of large-scale forcing or include long-lived, residual cloud products.

[13] The main underpredicted multi-type structures include cirrus combined with some type of lower cloud (middle, low, or both). Since any non-black cirrus layer would have the effect of lifting the emission level of the lower cloud types, those multi-type combinations have the potential to produce infrared emission levels in the middle troposphere. This, along with the fact that the ECMWF model forecasts actually overpredict single-type middle clouds, implies that the missing middle-level cloud found in the ECMWF evaluation study of *Tselioudis and Jakob* [2002], and potentially in other GCM evaluation studies against satellite observations, comes from the underprediction of multi-type cloud structures.

[14] The derived cloud type climatology from ARM SGP observations provided an additional insight into midlatitude cloud vertical structure deficiencies in ECMWF model simulations. The results point towards the simulation of multi-type cloud structures as the major source of the model cloud amount error. This gives an additional level of information in the effort to improve model cloud simulations. These structures occur mostly in atmospheric regimes of large-scale uplift or weak large-scale forcing [*Kollias et al.*, 2007], and further study is needed to understand the role of microphysical processes like the sublimation of falling cirrus ice [*Ryan et al.*, 2000] and dynamical processes like dry air intrusions [*Stewart et al.*, 1998] in the formation of multi-type cloud structures. The results of this study will be extended to the global domain and form a firmer base for GCM cloud layering evaluation when statistically significant data ensembles from CloudSat retrievals become available.

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References

Ackerman, T. P., and G. M. Stokes (2003), The Atmospheric Radiation Measurement program, *Phys. Today*, *56*, 38–44.

Clothiaux, E. E., T. P. Ackerman, G. G. Mace, K. P. Moran, R. T. Marchand, M. A. Miller, and B. E. Martner (2000), Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the ARM CART sites, *J. Appl. Meteorol.*, *39*, 645–665.

Dong, X., P. Minnis, T. P. Ackerman, E. E. Clothiaux, G. G. Mace, C. N. Long, and J. C. Liljegren (2000), A 25-month database of stratus cloud properties generated from ground based measurements at the Atmospheric Radiation Measurement Southern Great Plains site, *J. Geophys. Res.*, *105*, 4529–4538.

Jakob, C., R. Pincus, C. Hannay, and K.-M. Xu (2004), Use of cloud radar observations for model evaluation: A probabilistic approach, *J. Geophys. Res.*, *109*, D03202, doi:10.1029/2003JD003473.

Klein, S. A., and C. Jakob (1999), Validation and sensitivities of frontal clouds simulated by the ECMWF model, *Mon. Weather Rev.*, *127*, 2514–2531.

Kollias, P., E. E. Clothiaux, B. A. Albrecht, M. A. Miller, K. P. Moran, and K. L. Johnson (2005), The Atmospheric Radiation Measurement program cloud profiling radars: An evaluation of signal processing and sampling strategies, *J. Atmos. Oceanic Technol.*, *22*(7), 930–948.

Kollias, P., G. Tselioudis, and B. A. Albrecht (2007), Cloud climatology at the Southern Great Plains and the layer structure, drizzle, and atmospheric modes of continental stratus, *J. Geophys. Res.*, doi:10.1029/2006JD007307, in press.

Rossow, W. B., Y.-C. Zhang, and J. Wang (2005), A statistical model of cloud vertical structure based on reconciling cloud layer amounts inferred from satellites and radiosonde humidity profiles, *J. Clim.*, *18*, 3587–3605, doi:10.1175/JCLI3479.1.

Ryan, B. F., et al. (2000), Simulations of a cold front by cloud-resolving, limited-area and large-scale models and a model evaluation using in-situ and satellite observations, *Mon. Weather Rev.*, *128*, 3218–3235.

Stewart, R. E., K. K. Szeto, R. F. Reinking, S. A. Clough, and S. P. Ballard (1998), Midlatitude cyclonic cloud systems and their features affecting large scales and climate, *Rev. Geophys.*, *36*, 245–273.

Stokes, G. M., and S. E. Schwartz (1994), The Atmospheric Radiation Measurement (ARM) program: Programmatic background and design of the cloud and radiation test bed, *Bull. Am. Meteorol. Soc.*, *75*, 1202–1221.

Tselioudis, G., and C. Jakob (2002), Evaluation of midlatitude cloud properties in a weather and a climate model: Dependence on dynamic regime and spatial resolution, *J. Geophys. Res.*, *107*(D24), 4781, doi:10.1029/2002JD002259.

Wang, J., W. B. Rossow, and Y.-C. Zhang (2000), Cloud vertical structure and its variations from a 20-year global rawinsonde dataset, *J. Clim.*, *13*, 3041–3056.

Webb, M., C. Senior, S. Bony, and J. J. Morcrette (2001), Combining ERBE and ISCCP data to assess clouds in the Hadley Centre, ECMWF and LMD atmospheric climate models, *Clim. Dyn.*, *17*, 905–922.

Zhang, M. H., et al. (2005), Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements, *J. Geophys. Res.*, *110*, D15S02, doi:10.1029/2004JD005021.

P. Kollias, Atmospheric Science Division, Brookhaven National Laboratory, Building 490D, Bell Avenue, Upton, NY 11973, USA.

G. Tselioudis, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA. (gtselioudis@giss.nasa.gov)